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The Use of Homegarden Agroforestry Systems for Climate Change Mitigation in Lowlands of Southern Tigray, Northern Ethiopia

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Authors' contributions

This work was carried out in collaboration between both authors. Author GES designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author TT managed the analyses of the study. Both authors read and approved the final manuscript.

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ABSTRACT

Mitigation of climate change is one of the major environmental challenges facing the globe. In this context, homegarden agroforestry systems (HGAFs) have large potential for climate change mitigation. Therefore, this study was initiated to estimate the biomass and soil carbon stocks of HGAFs in relation to adjacent Natural Forest (NF). It also analyzed the relationship between woody species diversity, evenness and richness with biomass and soil carbon stocks. Three sites were purposely selected on the basis of the presence of HGAFs and NF adjacent to each other. Random sampling was used to select representative homegardens from the study population. In NF, a systematic sampling technique was employed. A total of 60 plots with a size of 10 m x 20 m were

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used to collect vegetation and soil data in both land uses. Soil samples were collected from each plot of the samples laid for vegetation sampling. Accordingly, 120 composite and 120 undisturbed soil samples from 0-30 cm and 30-60 cm soil depths were collected for soil organic carbon (SOC) and bulk density analysis respectively. Biomass estimation for each woody species was analyzed by using appropriate allometric equations. The result showed that the total amount of carbon stocks was 148.32±35.76 tons ha^{-1} and 157.27±51.61 tons ha^{-1} in HGAFs and adjacent NF respectively which did not vary significantly between the two studied land uses ($P > 0.05$). The finding also shows a positive but non-significant (P>0.05) relationship between carbon stocks and woody species diversity, richness, and evenness. Specifically, in NF lands, woody species diversity with SOC (r=0.36) and in HGAFs species richness with biomass carbon (r=0.39) was correlated positively and significantly (P=0.05). We concluded that HGAFs have the same potential as the NF for carbon stock accumulation and to counteract the loss of biomass.

Keywords: Carbon stocks; carbon sequestration; forest; soil organic carbon; woody species diversity.

1. INTRODUCTION

Climate change is an important environmental issue as it poses a global threat to sustainable development of human life [1]. It is a serious environmental issue affecting humans through its consequence on temperature increase, sea-level rise due to melting of glaciers and sea ice, changes in the location of appropriate habitat for plants and animals, amongst other. Mitigation of global warming is a major environmental challenge today [2]. Thus reducing global warming entails reducing the atmospheric concentrations of GHGs, particularly CO2. Such reductions are brought about by carbon sequestration, the process of removing carbon from the atmosphere and depositing it in a reservoir, or the transfer of atmospheric CO2 to secure storage in other long-lived pools [3].

According to FAO carbon stock is the quantity of carbon contained in a “pool”, meaning a reservoir or system which has the capacity to accumulate or release carbon. Carbon stock is the same as C sequestration: C sequestration is a rate. process involving the time factor (e.g., Mg C ha^{-1} $year^{-1}$), whereas C stock (Mg ha^{-1}) does not have the time factor [4]. Recently, carbon sequestration potential of agroforestry system has attracted attention from both industrialized and developing countries following the recognition of agroforestry climate change mitigation strategy under the Kyoto protocol [4–9].

In this context, HGAFs have large potential for climate change mitigation [10]. These systems are complementary land-use practices where climate change mitigation function can be enhanced while also supporting livelihoods [11]. Homegarden agroforestry systems are distinct from other forms of agriculture in their ability to store higher amounts of carbon in the biomass, soils and products [12]. Homegardens are planted and maintained by members of the household and their products are intended primarily for household consumption [13]. In most areas, HGAFs resemble natural forests in their important role in storing carbon besides its several benefits through supporting people’s livelihoods through offering energy, food and fiber [14]. Homegardens are also important in reducing the pressure of encroachment on natural forests (NF) and also enhance resilience to climate change [15].

In Ethiopia and particularly in Northern Ethiopia where this study was conducted, forests are very fragmented and restricted to inaccessible and sacred areas such as around churches [16]. On the other hand, trees retained or planted in HGAFs play an important role in delivering different products including food, fiber, energy, timber and medicine and mitigating climate change. However, there is limited quantified scientific evidence for HGAFs roles in ecosystem service such as carbon storage in northern Ethiopia. Therefore, this study aimed to investigate the contribution of HGAFs in maintaining carbon stocks compared to adjacent NF in the semi-arid climatic region of Raya Alamata Northern Ethiopia.

2. MATERIALS AND METHODS

2.1 Description of Study Area

This study was conducted in low lands of Raya Alamata, southern Tigray Northern Ethiopia (Fig. 1). It is geographically located between 12º19'21” N and 12º24'28” N latitude and 39º14'52” E and 39º45'47” E longitude.

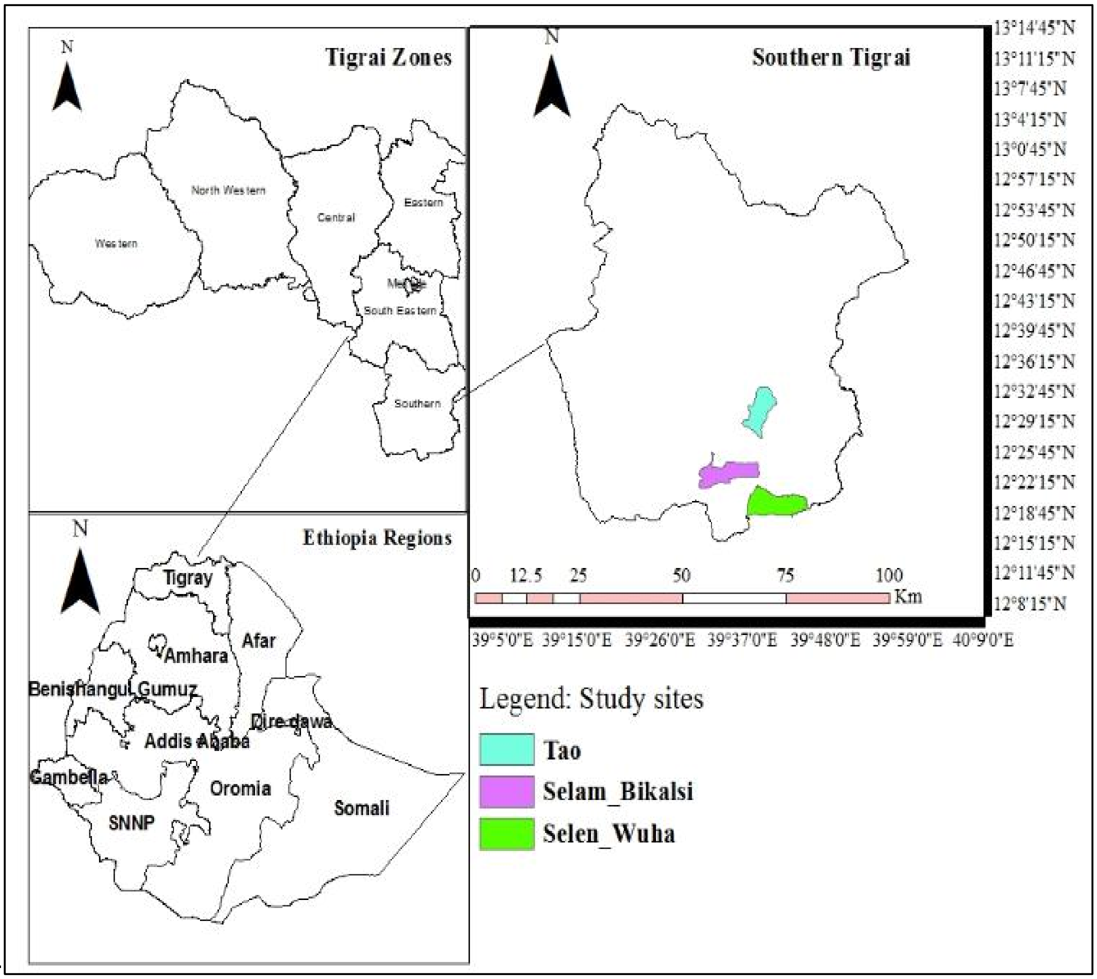

Fig. 1. Location of the study area in northern Ethiopia

The climate of the study area is arid with bimodal rainfall and mean annual rainfall 699.6 mm and ranging from 299 to 1067 mm, with a mean monthly minimum and maximum temperature of 15ºC and 27ºC respectively (NMA National Metreology Agency, 2016).

The dominant soil types of the study area are Eutric Vertisols, Lithic Leptosols and Lithic Leptosols [17]. Some of the soil physical and chemical properties of the study site were analyzed in the Mekelle soil laboratory center and described by taking the soil sample from the representative quadrats of each HGAFs and NF (Table 1). According to the soil laboratory, result soil profiles tested show that PH and bulk density increased with depth while percentage N decreased with depth in both land uses. The soil textural class was also found clay loam and loam for HGAFs.

2.2 Sampling Design and Data Collection

Three study sites (Tao, Selam-Bikalsi and Selen-Wuha) were purposely selected from the study area based on the existence of HGAFs adjacent to NF. Different wealth status and Age of the homegardens were considered to account for differences in woody species diversity and biomass, soil and total carbon stock. Inventory of woody species was undertaken from randomly selected homegardens with a quadrat size of 10 m x 20 m following Negash and Kanninen [18]. Whereas, systematic sampling using a transect line technique was used to collect data from NF. Five transect lines were laid at 450 m intervals parallel to the slope. The distance between quadrats on the transect line was 200 m. Similar to the sampling strategies used in HGAFs, 10 m x 20 m quadrats was used to collect data from NF [19,20].

Table 1. Mean (±SD) physical and chemical properties of soils in HGAFs and adjacent NF

Variable	Depth (cm)	Land use	
		HGAFs	NF
PH	0 -30	8.03(±0.40)	7.83 (±0.71)
	30 - 60	8.06(±0.26)	8.29(±0.31)
TN (%)	0 -30	0.14(±0.06)	0.16(±0.06)
	30 - 60	0.12(±0.03)	0.11 (±0.02)
BD (g/cm^3)	0 -30	1.13(±0.12)	1.14(±0.10)
	30 - 60	1.17(±0.12)	1.18(±0.11)
Sand %	0 -30	36.28(±6.18)	39.07(±8.07)
	30 - 60	26.5(±9.79)	38.00(±7.05)
Silt %	0 -30	35.89(±6.26)	38.13 (±8.57)
	30 - 60	38.5 (±6.32)	38.67 (±6.53)
Clay %	0 -30	27.83(±3.62)	22.80(±6.67)
	30 - 60	35(±10.30)	23.33(±6.53)
Soil texture class	0 -30	Clay Loam	Loam
	30 - 60	Clay Loam	Loam

Where: SD is standard deviation

Data were collected from a total of 60 quadrats (30 from HGAFs and 30 from NF). Biometric parameters such as diameter at breast height (DBH) ≥ 2.5 cm and height ≥1.5m were measured and recorded in all sample quadrats. Woody species found on the border of the plot were only included when more than 50% of their basal area falls within the plot [20]. Trees forking below DBH were separately measured at breast height and the overall DBH of the forks determined as the square root of the sum of squares of individual stems [21].

Soil samples were collected from each plot of the quadrats that accommodating vegetation sampling in both land use type (i.e., HGAFs and NF land use type). The soil samples were collected within 1 m x 1 m ($1m^2$) sub-plots in the quadrat, from the top left and bottom right corners and one in the middle. Two separate soil samples were collected for the analysis of soil organic carbon (SOC) contents and soil bulk density. In each case, samples were collected from two depths of 0–30 and 30–60 cm. In one of the three subplots randomly selected, an undisturbed soil was taken through core sampling to determine bulk density using core sampler to determine the bulk density [22]. The soil samples for SOC analysis were collected using soil augur. Three soil samples were taken from the three $1m^2$ sub-plots of the quadrant and then for each depth composite was prepared according to the depth of sample drawn [22]. The total number of soil samples from both land uses was 120 (60 for HGAFs and NF each) for SOC analysis and similarly, 120 (60 for HGAFs and NF each) samples were also collected for bulk density.

2.3 Data Analysis

2.3.1 Biomass carbon stock

The above-ground biomass (AGB) of trees and shrubs were calculated using the plot inventory data and allometric model. Both species-specific and general allometric models were used to estimate the AGB (Table 2).

The general model of Kuyah [23] was adopted because it is established in Malawi, which has a similar climatic condition to the study area. In addition, the model was developed using woody species from agroforestry practices and woodlands with 98% of trees having DBH of less than 40 cm which fits very well with the data from this study.

To convert the AGB to carbon, the default value of 50% (Formula 1) was used for trees and shrubs biomass was assumed to be the carbon stock [24]. Consequently, the AGB of trees and shrubs' carbon stock calculated as:

Formula 1: $\mathrm{AGC} = \mathrm{AGB} * 0.50$

Where; AGC: Aboveground carbon stock for woody species (Kg/tree)
AGB: Aboveground biomass for woody species (Kg/tree)

Below ground dry biomass of the woody species (BGB) was determined as 27% of the above-ground biomass [25] and accordingly 50% for trees and shrubs were also adopted for its carbon estimation Formula 2 and Formula 3 respectively.

Table 2. Allometric equations used to estimate the aboveground biomass of woody species

Species	Allometric equation	R^2	Sources
Olea europaea	$1.089*DBH^{1.684}$	0.94	[26]
Coffea arabica	$0.147*D^2$	0.80	[27]
Eucalyptus species	0.085*DBH 2.471	0.95	[28]
Mangifera Indica	-2.43 + 0.154 DBH + 0.193 H	0.96	[29]
Balanites aegyptiaca and *Acacia seyal*	$1.929\ DBH + 0.116\ (DBH)^2 + 0.013\ (DBH)^3$	0.93	[30]
Other species (general)	$0.1428*DBH^{2.2471}$	0.95	[31]

Where; DBH: Diameter at breast height (cm); d: is the diameter at stump height (DSH) at 40cm

Formula 2: $\mathrm{BGB} = \mathrm{AGB} * 0.27$

The carbon stock for a belowground component of trees and shrubs had measured as follows

Formula 3: $\mathrm{BGC} = \mathrm{BGB} * 0.50$

Where; BGC: Belowground carbon stock for woody species (Kg/tree)
BGB: Belowground biomass for woody species (Kg/tree)

Therefore, the total biomass carbon stock for woody species (Formula 4) was calculated by summing above-and below-ground biomass carbon stock for woody species for each plot and the average of all plots has converted to hectare as follows:

Formula 4: $\mathrm{T\ BC\ (tone\ C\ ha^{-1})} = (\mathrm{Woody\ AGC} + \mathrm{Woody\ BGC}$

Where; T BC: Total biomass carbon stocks for woody species (tone ha-1)
AGC: Aboveground biomass carbon stocks for woody species (tone ha-1)
BGC: Belowground biomass carbon stocks for woody species (tone ha-1)

2.4 Soil Analysis

The soil sample was taken in January 2017. The collected soil samples for soil bulk density analysis were initially air-dried and oven-dried at 105ºC for 48 hours. The bulk density was calculated according to Formula 5:

Formula 5: $\rho\mathrm{b}\ \left(\frac{\mathrm{g}}{\mathrm{cm3}}\right) = \frac{ODW}{\mathrm{CV}-(\frac{RF\ (g)}{PD(\frac{\mathrm{g}}{\mathrm{cm3}})})}$

Where: ρ_b = Bulk density of the < 2 mm fraction
ODW = Oven-dry mass of fine fraction (<2 mm)
CV = Core volume
RF = Mass of coarse fragments (> 2 mm)
PD = Density of rock fragments. This often is given as 2.65 g/cm^3.

The soil samples collected for analysis of SOC were air-dried, homogenized and ground sieved with a 2 mm mesh size sieve [32]. SOC per plot and then per hectare was calculated as the Formula 6 below:

Formula 6: $\mathrm{SOC} = [(\ \rho\mathrm{b}\left(\frac{g}{cm3}\right) * D\ (cm) * \%C)]$

Where: SOC = Soil organic carbon [tone ha^{-1}]
% C = Organic carbon concentration of the plot [%] expressed in decimal
ρ_b = Bulk density of the plot [g/cm^3]
D = Depth of the soil sample [cm]

The SOC stock values for the two depths (0–30 cm and 30–60 cm) were summed to give the SOC stock for the total 0–60 cm depth.

The total nitrogen (N) was analyzed using the Kjeldhal method [33] and Soil pH was measured with combined electrodes in a 1:2.5 soil to water suspension.. Soil texture was determined by using hydrometer method [34].

2.5 Ecosystem Carbon Stocks

The total carbon stock of the land uses was calculated by summing total biomass carbon stock and soil organic carbon (0-60 cm).

2.6 Relationship between Woody Species Diversity and Carbon Stocks

The Shannon-Wiener and Shannon evenness were used to analyze the diversity of woody species and evenness using Krebs [33]; Magurran [34]

Formula 7 and Formula 8.

Shannon index calculated by multiplying the abundance of a species (pi) by the In of this number:

Formula 7: $\mathrm{H}' = -\sum_{i=1}^{s} \mathrm{Pi}\ln(\mathrm{Pi})\, q.$

Where: H'= Shannon diversity indices
Pi= proportion of individuals found in the ith species.

The equitability/ evenness were calculated as the ratio of observed Shannon index (H') to maximum diversity (Hmax). The formula used to calculate equitability /evenness is as follows:

Formula 8: $\text{Equitability (evenness)}J = \frac{H'}{H'max} = \frac{-\sum_{i=1}^{s} \text{Pi} \ln pi}{\ln s}$

Where S = the number of species
H'=, Shannon diversity indices and
P_i = proportion of individuals found in the i^{th} species.

2.7 Statistical Analysis

Prior to further statistical analysis, the normality of the distribution of data sets was tested using the Shapiro-Wilk test If normality was not met, data were transformed in log values. F test and Leven's test was used to calculate the homogeneity of variance of the data. Difference between means was estimated by using a t-test, in case, where the data was not found to be homogenous, the Kruskal-Wallis test was used. The Spearman correlation coefficients correlation was used to analyze the relationship between woody species diversity and carbon stocks. The statistical analysis was done by using the R software program (version 3.3.4.) (R core team 2018).

3. RESULTS

3.1 Biomass Carbon Stocks

Higher and significant differ (*P* = 0.05) amount of average biomass carbon was recorded in NF as compared to HGAFs in all studied sites (Table 3).

3.2 Soil Carbon Stock (SOC)

The total (0-60 cm depth) SOC of the study area in HGAFs and the adjacent NF were not statistically different (Table 4). However, the average surface layer (0-30 cm) SOC significantly differed within each HGAFs and NF (*P* <0.001). The top surface layer accounted for 58% and 63% of the total SOC in HGAFs and adjacent natural forests respectively.

3.3 Total Carbon Stock Potential

The total amount of carbon stock, consisting of woody above ground carbon, woody below ground biomass carbon and soil organic carbon, was 148.32 ±35.76 tons ha^{-1} and 157.27 ±51.61 tons ha^{-1} in HGAFs and adjacent NF respectively (Fig. 2). The results showed that the overall total carbon stock did not vary significantly between the two studied land uses (*P* > 0.05).

Table 3. Mean (±SD) above and below ground carbon stock of both HGAFs and adjacent NF land uses (tons ha^{-1})

Variables	HG AF(N=30)	NF(N=30)	P value
AGCS	30.37 (±24.68) ^{a}	39.59 (±23.42) ^{b}	0.03
BGCS	8.20 (±6.67) ^{a}	10.69(±6.32) ^{b}	0.03
T BCS	38.57(±31.34) ^{a}	50.27 (±29.75)^{b}	0.03

Different letters in the same row are significantly different (P = 0.05). AGCS = above-ground woody biomass carbon stocks; BGC = below-ground woody biomass carbon stocks and T BCS = Total biomass carbon stocks

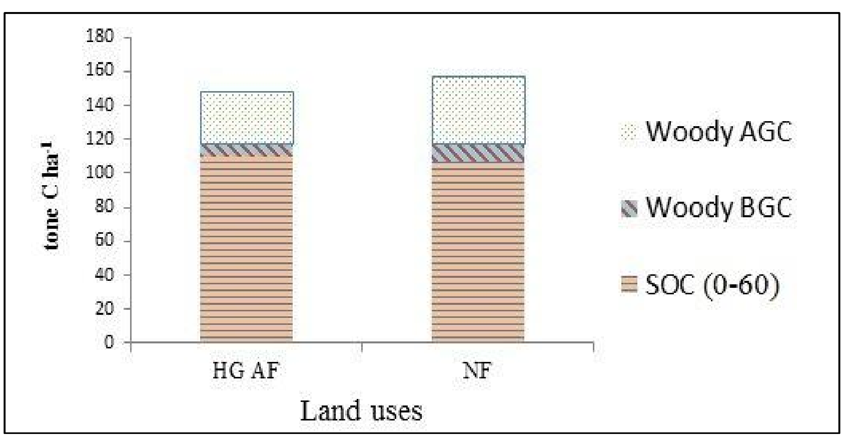

Fig. 2. Biomass and soil carbon stock of HGAFs and adjacent NF

Table 4. Mean soil organic carbon (±SD, tons ha^{-1}) of the studied HGAFs and adjacent NF

Variable	Depth (cm)	HGAFs(n=30)	NF(n=30)
SOC ton ha^{-1}	0 - 30	63.50 (±16.86)^{b}	67.09 (±24.96)^{b}
	30 - 60	46.25 (±16.90)^{a}	39.91(±15.96)^{a}
	Total (0-60)	109.75 (±29.95)^{a}	107.00 (±35.64) ^{a}

Different letters in the column show the significant difference with in the land use and similar letters in the same row show non-significant differences (p = 0.05)

Table 5. Correlations of carbon stocks (ton ha^{-1}) and woody species parameters in HGAFs and adjacent NF

Carbon stocks	HGAFs (n=30)						NF (n=30)					
	H'		Spp r		Evenness		H'		Spp r		Evenness	
	r	p	r	p	r	p	r	p	r	p	r	p
Biomass	0.46	0.41	0.39	0.03*	0.4	0.31	0.23	0.22	0.03	0.89	0.36	0.51
SOC(0-60 cm)	0.04	0.83	0.03	0.86	0.09	0.65	0.36	0.05*	0.23	0.22	0.31	0.10
Ecosystem	0.4	0.73	0.37	0.85	0.34	0.07	0.11	0.55	0.21	0.26	0.06	0.76

*Where, H'; Shannon diversity, Spp r: Species richness. * is significantly different at (P =0.05)*

3.4 Relationship between Woody Species Diversity and Carbon Stocks

The result of woody species diversity with Biomass and Ecosystem carbon stocks showed no relation ($P > 0.05$) at both land use types but Shannon diversity which combines richness and abundance was significant ($P = 0.05$) with total SOC carbon stocks at NF land use (Table 5).

4. DISCUSSION

4.1 Biomass Carbon Stocks

The lower biomass carbon stock of HGAFs relative to NF in this study is due to the smaller mean DBH (i.e. 12.93cm±5.59cm SD) of the woody species of HGAFs as compared to NF which has woody species with a higher average diameter (i.e. 22.33cm±8.86cm SD).

The carbon stock of HGAFs reported in this study is within the range of 12 - 228 tons carbon ha^{-1} reported for tropical agroforestry [4]. Several studies [12,35,36] in the tropics reported similar findings. However, the present result was higher than the study in homegardens of Mwanga district, Kilimanjaro, Tanzania [37], but lower than the carbon stock reported in the southern Ethiopia [38]. The biomass carbon stock could vary depending on the age of the trees, types of species, management and biophysical conditions [39-41]. The difference in the type of allometric equation used to estimate biomass might also explain the difference in estimated values of carbon stock in different studies [42].

4.2 Soil Carbon Stock

The total SOC (0-60 cm depth) in HGAFs and adjacent NF of the study area were not significantly different. This shows that HGAFs can maintain the same level of soil organic carbon in relation to the adjacent NF. The biomass of litter fall and fine roots contributes to carbon stock accumulation in soil. It is the most important known pathway connecting vegetation and soil, and is a good indicator of aboveground productivity [43]. This result of SOC in both land uses was in line with the worldwide mean SOC stocks of 106 tons C ha^{-1} [43].

The present study in HGAFs was higher than those recorded in homegarden of Gununo watershed agroforestry practices (SOC 61.57±11 tons ha^{-1}) in southern Ethiopia [38] and Indonesian homegarden systems (SOC 60.8 tons ha^{-1}) reported by Roshetko [35]. However, it was lower than the finding of Negash and Kanninen [41] in three indigenous agroforestry systems in south-eastern Rift valley escarpments of Ethiopia (179-186 tons ha^{-1}). Several factors such as soil types, climate, decomposition rates, and management strategies affect SOC stocks in different areas [44]. In addition to the above, the qualities of the SOM, soil pH, soil temperature also affect the SOC stocks. For instance, land management practices such as the removal of plant biomass and tillage can decrease carbon input from litterfall and root exudates [45]. Besides, tillage reduces the physical protection of soil organic matter from decomposition because of the destruction of soil structure, which enhances the microbial decomposition of labile carbon [46].

4.3 Total Carbon Stock Potential

The result of this study showed the total carbon stock of HGAFs is the same level as the adjacent NF. This shows that HGAFs has the potential to store carbon in a similar magnitude with NF in addition to supporting livelihoods. Hence, like other land use options, HGAFs have real potential to contribute to climate change mitigation and also preserving and strengthening the environmental ecosystem. It (HGAFs) has a key role to play in landscape-scale mitigation schemes under the REDD+ (Reduce Emissions from Deforestation and forest Degradation in developing countries) or AFOLU (Agriculture, Forestry, and other land uses) concepts [47].

From the total carbon stock, soil organic carbon (SOC) (0-60 cm) contained the greatest amount of carbon followed by woody AGC and BGC. On average, 74% of the carbon stock in HGAFs plots was found in SOC, 21% woody AGC, and 5 % in woody BGC (Appendix 1). The distribution of carbon in NF plots followed a similar trend to HGAFs plots, with 68% of the carbon stored in NF plots was found in SOC (0-60cm), 25% woody AGC, and 7% in Woody BGC (Appendix 2). This result is in line with other findings [48,49] that reported about three times more carbon in soils than in biomass.

4.4 Relationship between Woody Species Diversity and Carbon Stocks

In HGAFs and adjacent NF woody species diversity and species evenness were positively correlated with SOC, biomass, and ecosystem carbon tons ha^{-1}. This is in line with the finding of other studies [50,51] reported that land uses with two or more woody species may achieve higher levels of productivity than single-species. If species mixes involve complementary resource use and facilitation of tree growth of one species by the other, it leads to positive impacts on belowground carbon sequestration through litterfall and root exudation. This results is in line with the findings that reported a positive and significant correlation between woody species richness and soil carbon stock in the lowlands of Tigray, Ethiopia [52] and South-eastern Rift Valley escarpment, Ethiopia [18]. Similar to Kerala, India [53] and Terai forest in Nepal [54] our study also showed a positive and significant correlation between woody species richness and SOC in homegarden. The general trend is that ecosystems with high woody species diversity sequester more carbon in the soil than those that have a lower diversity [48].

The positive correlations in HGAFs of biomass, SOC and ecosystem carbon stocks with woody species richness, diversity and species evenness show that these components are important in storing soil organic carbon in addition to other environmental conditions and age of HGAFs. These relationships suggest that the loss of biodiversity may damage the functioning of ecosystems and thus diminish the number and quality of services (e.g. carbon storage) they provide.

5. CONCLUSION

The total biomass and soil carbon stocks (total carbon stock) of HGAFs were similar to the adjacent NF, implying that homegardens are potential ecosystem for accumulation of carbon stocks. Our study also revealed that there was a positive relationship between carbon stocks and woody species diversity, species richness and species evenness in both land uses; this suggests that there is a connection among activities to conserve biodiversity and carbon stocks may exist.

Thus, our study concluded that HGAFs of the study area, which supports livelihoods and provides food, is essential for C sinks to help in climate change mitigation which is comparable with natural forest. As recommendation HGAFs are a better option in the degraded lands of Northern Ethiopia in reducing greenhouse gas emissions (GHG) and it should be considered in carbon sequestration schemes such as the REDD+ and CDM.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Appendix 1. Carbon stock results of Homegarden Agroforestry (HGAF) in Raya Alamata, southern Tigray, Ethiopia

No.	Site	Plot no.	AG and BG C tone per ha				Ecosystem CS tone ha^{-1}
			AGCS tone ha^{-1}	BGCS ha^{-1}	TBCS tone ha^{-1}	SOC (0-60) tone ha^{-1}	
1	Ta'o	1	5.06	1.37	6.42	88.98	95.40
2	Ta'o	2	12.64	3.41	16.06	137.46	153.52
3	Ta'o	3	32.12	8.67	40.79	169.58	210.37
4	Ta'o	4	15.83	4.27	20.10	163.16	183.26
5	Ta'o	5	30.54	8.25	38.79	83.28	122.06
6	Ta'o	6	5.92	1.60	7.52	142.25	149.77
7	Ta'o	7	35.72	9.65	45.37	120.47	165.84
8	Ta'o	8	16.72	4.51	21.24	153.97	175.21
9	Ta'o	9	16.85	4.55	21.40	112.73	134.12
10	Ta'o	10	30.44	8.22	38.65	132.67	171.32
11	Selam Bikalsi	1	64.50	17.41	81.91	82.69	164.61
12	Selam Bikalsi	2	108.51	29.30	137.81	78.29	216.10
13	Selam Bikalsi	3	16.93	4.57	21.51	108.83	130.34
14	Selam Bikalsi	4	10.03	2.72	12.75	88.50	101.25
15	Selam Bikalsi	5	7.83	2.12	9.95	139.06	149.01
16	Selam Bikalsi	6	36.39	9.83	46.22	108.83	155.05
17	Selam Bikalsi	7	10.70	2.89	13.59	122.77	136.36
18	Selam Bikalsi	8	53.24	14.37	67.61	76.13	143.74
19	Selam Bikalsi	9	19.92	5.38	25.30	136.22	161.52
20	Selam Bikalsi	10	36.88	9.96	46.84	144.52	191.36
21	Selen Wuha	1	50.58	13.66	64.24	42.91	107.15
22	Selen Wuha	2	45.72	12.34	58.06	90.13	148.20
23	Selen Wuha	3	20.24	5.46	25.70	103.52	129.22
24	Selen Wuha	4	19.39	5.23	24.62	101.11	125.74
25	Selen Wuha	5	12.02	3.25	15.27	78.82	94.09
26	Selen Wuha	6	73.32	19.80	93.11	120.77	213.89
27	Selen Wuha	7	11.30	3.05	14.35	89.24	103.60
28	Selen Wuha	8	15.17	4.09	19.26	101.82	121.08
29	Selen Wuha	9	18.75	5.06	23.81	76.67	100.48
30	Selen Wuha	10	77.77	21.00	98.77	97.07	195.84
Average tone ha^{-1}			30.37	8.20	38.57	109.75	148.32
% from the total CS			21	5		74	

Where, CS: carbon stock, AG: Above ground, BG: Below ground, TB: Total biomass

Appendix 2. Carbon stock results of Natural Forest (NF) in Raya Alamata, southern Tigray, Ethiopia

No.	Site	Plot no.	AG and BG C tone per ha				Ecosystem CS tone ha^{-1}
			AGCS tone ha^{-1}	BGCS ha^{-1}	TBCS tone ha^{-1}	SOC (0-60) tone ha^{-1}	
1	Ta'o	1	5.06	1.37	6.42	88.98	95.40
2	Ta'o	2	12.64	3.41	16.06	137.46	153.52
3	Ta'o	3	32.12	8.67	40.79	169.58	210.37
4	Ta'o	4	15.83	4.27	20.10	163.16	183.26
5	Ta'o	5	30.54	8.25	38.79	83.28	122.06
6	Ta'o	6	5.92	1.60	7.52	142.25	149.77
7	Ta'o	7	35.72	9.65	45.37	120.47	165.84
8	Ta'o	8	16.72	4.51	21.24	153.97	175.21
9	Ta'o	9	16.85	4.55	21.40	112.73	134.12

No.	Site	Plot no.	AG and BG C tone per ha				Ecosystem CS tone ha^{-1}
			AGCS tone ha^{-1}	BGCS ha^{-1}	TBCS tone ha^{-1}	SOC (0-60) tone ha^{-1}	
10	Ta'o	10	30.44	8.22	38.65	132.67	171.32
11	Selam Bikalsi	1	64.50	17.41	81.91	82.69	164.61
12	Selam Bikalsi	2	108.51	29.30	137.81	78.29	216.10
13	Selam Bikalsi	3	16.93	4.57	21.51	108.83	130.34
14	Selam Bikalsi	4	10.03	2.72	12.75	88.50	101.25
15	Selam Bikalsi	5	7.83	2.12	9.95	139.06	149.01
16	Selam Bikalsi	6	36.39	9.83	46.22	108.83	155.05
17	Selam Bikalsi	7	10.70	2.89	13.59	122.77	136.36
18	Selam Bikalsi	8	53.24	14.37	67.61	76.13	143.74
19	Selam Bikalsi	9	19.92	5.38	25.30	136.22	161.52
20	Selam Bikalsi	10	36.88	9.96	46.84	144.52	191.36
21	Selen Wuha	1	50.58	13.66	64.24	42.91	107.15
22	Selen Wuha	2	45.72	12.34	58.06	90.13	148.20
23	Selen Wuha	3	20.24	5.46	25.70	103.52	129.22
24	Selen Wuha	4	19.39	5.23	24.62	101.11	125.74
25	Selen Wuha	5	12.02	3.25	15.27	78.82	94.09
26	Selen Wuha	6	73.32	19.80	93.11	120.77	213.89
27	Selen Wuha	7	11.30	3.05	14.35	89.24	103.60
28	Selen Wuha	8	15.17	4.09	19.26	101.82	121.08
29	Selen Wuha	9	18.75	5.06	23.81	76.67	100.48
30	Selen Wuha	10	77.77	21.00	98.77	97.07	195.84
Average tone ha^{-1}			39.59	10.69	50.27	107.00	157.27
% from the total CS			25	7		68	

Where, CS: carbon stock, AG: Above ground, BG: Below ground, TB: Total biomass

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